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13. ABSTRACT
We studied soliton based gigabit networks with an emphasis Air Force interests. We sought parallel data streams with a precise temporal relationship between envelopes and carrier phases of the pulses. We examined nonlinear interactions that stabilize the temporal relationship of pairs of pulses propagating on similar, but physically distinct optical paths. We constructed a simple local area network having~4 km of single mode dispersion shifted fiber operating at 1.53 microns and 1.36 GHz. We explored dual core fiber. We found a practical barrier in the uncontrolled variations in the relative optical path delay in the two cores. As a means of obtaining greater control over short optical pulse parallel data streams we explored an adjustable temporal delay caused by a compact periodic semiconductor structures. We reduced the group velocity of a 2 psec pulse to 1/18th the free space velocity in an adjustable manner in an 8 micron thick GaAs/AlGaAs structure. The losses were as little as 5% and negligible pulse distortion occurred. We also used numerical simulations to explore the dynamics of enhanced nonlinear optical pulse interactions in microresonators. The latter efforts are useful in addressing practical barriers encountered in this work.

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2. Table of Contents

Introduction

3.1 Proposed work.

The work proposed under this grant is to explore soliton-like phenomena as they apply to gigabit networking relevant to Air Force interests. A primary concern is to explore means of realizing parallelism of data streams where soliton -like mechanisms maintain not only the properties of optical pulses, but also temporal relationship of the envelopes and carrier phases of pulses propagating in parallel. A long term goal is agile control of the envelopes and carrier phases of the pulses forming the array of data streams.

Part of the work was to be directed to using nonlinear optical interactions and active feedback stabilization to produce highly stable bit streams of solitons. Part of the work was to explore use of nonlinear optical interactions to stabilize the temporal and spatial relationship of solitons traveling on optical paths that were similar, but spatially distinct. We also proposed a simple on campus working network operating at gigabit rates where the optical pulses propagated on single mode fiber approximated solitons.

3.2 Motivation for the work

The overall goal is to enhance information acquisition, transmission, and processing in applications of interest to the U.S. Air Force. A long term goal for this effort is agile optical phased arrays in a compact robust technology suitable for field deployment where no mechanically moving parts are needed. The basic immediate task is to develop reliable methods for stabilizing and controlling the envelopes and carrier phases of pulses traveling on similar, but physically distinct paths.

Key physics of interest are the nonlinear interaction of short optical pulses traveling on similar, but physically distinct optical paths. that operate to stabilize the temporal and spatial relationship of two or more ultrashort pulses. In general, it is difficult to synchronize two optical pulses traveling on physically distinct optical without either a dedicated structure that is very rigid and stable, or active feedback stabilization, or some strong nonlinear interaction that favors the synchronized condition. It is even more difficult to maintain the optical carrier fields for two pulses phase locked, i.e., having optical carrier fields that retain an interferometrically stable relationship. Our goal is to seek strategies for actively maintained structures and nonlinear phenomena that provide precision, stability, and agility in combination.

We experimentally observed such synchronization of the envelopes, and also, on occasion, the phases, for pulse pairs where each pulse propagated on an optical path that was similar to that of the other, but physically distinct. The two paths were formed in modelocked dye laser oscillators that shared a common saturable absorber. Mechanical adjustment of the relative path length and nonlinear interactions where used to accomplish this condition. This work is encouraging, but the dye laser technology is not practical for Air Force field applications. Hence our interest in studying this phenomena in more robust and more agile solid state laser media without a need for significant mechanical motion.

We reasoned that if a similar nonlinearly induced synchronization, and phase locking, could be achieved in solid state modelocked lasers structured in arrays of optical guides this might form the basis for a practical agile optical phased array technology. The line of thinking is that solid state technology can be relatively robust and provides access

to a rapidly evolving set of technology for modulation, pulse forming, coupling, switching, amplification, and other related capabilities. In particular, we sought to explore this technology in a manner that involved both university and Air Force Laboratory personnel.

3.3 Structuring of the work

The work has been structured into several stages of increasing difficulty. The first step was to achieve stable, but adjustable, relationships of the pulse envelopes and optical carrier phase for solitons traveling on the same optical path. The approach here is to use active feedback stabilization and nonlinear optical mechanisms to achieve envelope and phase stability for an extended sequence of pulses in a ring laser geometry. Any practical system will require control and stability of the pulses over an extended period of time. As a beginning step each pulse and also the pulse train must be intrinsically stable.

The second level of difficulty, also addressed under this grant, is that of using linear and nonlinear optical interactions to achieve stable, but adjustable, envelope and phase relations of solitons traveling on similar, but physically distinct optical paths. This task is made difficult by the inevitable presence of small differences in the optical pathlength for similar, but physically distinct optical paths. These differences are typically of the order of a fraction of an optical wavelength or more in systems not specially designed to be highly uniform. These small random differences tend to dephase the optical carrier fields and cause a significant loss in capability. This is a problem that must be solve if successful agile optical phased arrays are to be achieved.

A third level of difficulty, essential to agile optical phased arrays, is the development of a capability to rapidly and reliably change the relationship of the envelopes and phases of solitons in physically distinct data streams. We did not initially intend to pursue this task under the present grant. We did, however, have an opportunity for a collaborative effort that achieved some success this area. In this work we constructed an adjustable optical delay line using photonic band edge phenomena. It is hoped that further promising paths for this third level of effort will be identified and pursued.

3.3.1 Key features of the effort.

Four key features in the proposed effort were: (1) Construction of a simple, but functioning, soliton based optical fiber network on the Rensselaer Polytechnic Institute campus, (2) construction of a harmonically modelocked laser[2,3] as a source of solitons at 1.55 microns at gigabit rates stabilized by active feedback control, (3) use of nonlinear optical interactions to produce short pulses at 1.55 microns, reduce pulse duration as needed, and maintain the stability of the pulse envelope and pulse train, and (4) exploration of techniques for stabilizing and controlling the relative temporal position of solitons traveling on similar, bur physically distinct, optical paths as in dual core fiber[4-6].

The four goals listed above were accomplished in significant degree. In addition lessons were learned regarding the generation and maintenance of arrays of synchronized and phase correlated ultrashort optical pulses. Construction of a feedback stabilized laser and a move from Rensselaer Polytechnic Institute to the University of Alabama in Huntsville were included in the period of the grant. We did not have an opportunity to explore applications in significant degree.

The numerical simulations, performed largely by Dr. Joseph Haus and students jointly supervised with Dr. Haus, showed that: (1) phase differences very small compared to an optical period are not very serious, but cumulative phase differences of the order of an optical period have dramatic consequences (2) mechanisms can be identified that keep a given soliton on a single core while under the same conditions low intensity optical noise couples to the adjacent guide where, e.g., it can be preferentially discarded, (3) that two solutions on adjacent cores, while oscillating around their common center of gravity, remain in a bound attractive state, and (4) conditions of neutral coupling where solutions on adjacent cores neither attract or repel can be found.

3.3.2 Problems identified, but not solved.

A key experimental finding was that dual[4], and hence multicore fiber, in general, exhibits a variation in the relative optical delay on different cores that is large compared to an optical period over distances of a centimeter or more. Since the characteristic lengths needed in fiber for most nonlinear processes are long compared to a centimeter stabilization does not appear achievable without substantial improvements in uniformity of the phase delay or the nonlinear coefficient, or both. It is not clear that even if the fiber structures were produced with ideal uniformity that small temperature differentials might not still cause serious dephasing over the distances of interest.

The numerical simulations also showed that there is no obvious nonlinear behavior in conventional dual core fiber that would override the consequences of random differences even given a large nonlinear coefficient. This does not imply that there is no solution. On the contrary the richness of phenomena is encouraging. The point to be made is that successful solutions will probably require some non-trivial degree of innovative effort.

3.3.3 Feasibility of synchronous parallelism

In essence we find that there are significant barriers to the achievement of agilely adjustable synchronous parallelism. At the same time we find that reducing optical delay irregularities, using active feedback stabilization, and finding. beneficial nonlinear interactions offer real opportunities. These barriers and opportunities are discussed in greater detail below.

3.4 Lessons learned

Important lessons were learned as regards the most favorable strategies: (1) in general, physically distinct paths should be kept as short as possible, (2) Nonlinear interactions that favor synchronization of the pulse envelopes and carrier fields should be made as large as possible, (3) structures that further favor synchronization and stable, but adjustable temporal envelope relationships are needed, (4)where relatively long physically distinct paths cannot be avoided, techniques are needed that will keep the net differential uncontrolled phase delay small. In the absence of unusually precise and stable material and device properties, any relatively long, spatially distinct, optical paths, must be through free space or at least through paths that are actively controlled. Where unintentionally introduced nonuniformities occur in the various optical paths there needs to be some means of correcting in real time the differential optical delays so introduced.

The main difficulty in achieving agile optical phased arrays appears to be that such arrays require a combination of agility and stability that, while not forbidden by basic physical laws, is not easily accessed with conventional technology. This goal does not appear to be inaccessible, but will probably require novel and effective use of combined active feedback stabilization, enhanced nonlinear interactions, compact device construction, and perhaps physical phenomena that are yet not fully understood.

3.5 Unexpected advances

3.5.1 Adjustable compact optical delay with minimal distortion and loss

An unexpected advance was achieved with some support from thisgrant.[7] This advance bears on the overall goal of an agile optical phased array. We were able to identify and evaluate novel physics and technology that provides an adjustable optical delay line for the short optical pulses. Key advantages of this optical delay line are that it is very compact, produces large group delay, and causes little pulse distortion or loss. Part of the delay line work was included in the effort carried out under this grant since on overriding need is providing means to electrically produce large group delays for a short optical pulse without introducing significant distortion or loss for the short pulse.

3.5.2 Enhanced nonlinear interactions

Another topic that we addressed in the course of this work was the role of exciton-polariton interactions in microresonators. One of the clear needs implied by the early part of this effort was for a strong nonlinear interaction in a relatively short length of material. One of the most promising phenomena of this kind is the exciton-polariton interaction in microresonators. Very large vacuum Rabi splittings have been observed for exciton-polariton states in microresonators.[8] There is evidence that suggests that these states could be realized in a variety of circumstances.

Some effort was invested in clarifying the nature of these phenomena. We would like to experimentally explore these states and determine whether they might be used to achieve some of the envelope and phase stabilization that we seek for the optical phased array work. As an initial step we devised a model of the state dynamics and carried out some numerical simulations of dynamical behavior. These models represent known experimental observations relatively well and provide us with some models to be tested experimentally.

4. Work performed at Rensselaer Polytechnic Institute

4.1 Optical fiber network

One of the experimental tasks that was taken up early in this effort was the construction of an operating single mode fiber network on the Rensselaer campus. The source laser was housed in the Center for Industrial Innovation. Fiber links were run to a junction box in the Jonsson Engineering Center and then to locations in the Physics building and other locations in the Jonsson Engineering Center. Fig. 1 shows a schematic of the network. About 4 km of dispersion shifted single mode fiber was installed.

One link in the Jonnson Engineering Building was run to the Microwave Laboratory of Jose Borrego where work on high performance electronic circuits was being carried out. A second link was run to an educationally oriented lecture/laboratory in the Physics Building. A third link was to be run to the multiphase fluid flow laboratory of Professor Richard Lahey; however, this application was not developed during the period at Rensselaer Polytechnic Institute other than to prepare the initial connections.

The fiber for the network was donated by Corning Inc. The cabling of the bare fiber was done by the Mohawk cabling company. Rensselaer Polytechnic Institute paid for the pulling of the fiber. The fusion splicing of the fiber was performed by students working with the Ultrafast Laboratory. Pulses with durations in the picosecond time domain were sent over the fiber and used to study the influence of the several kilometer path on the pulses. Demonstrations of the technology were performed for students and visitors as a means of encouraging support for the effort.

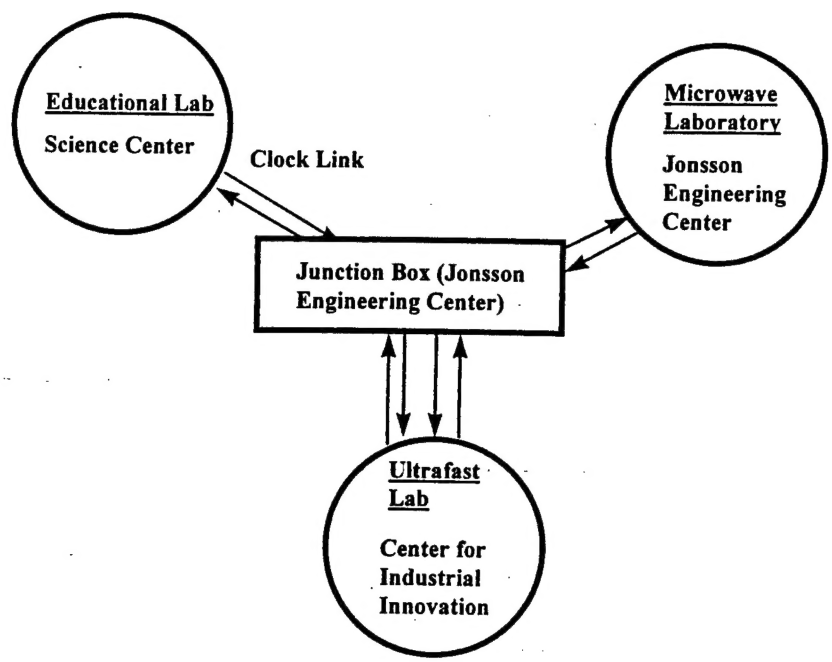

Fig. 1 Simple single mode dispersion shifted optical fiber network on the RPI campus.

The results were: (1) Expertise was developed in designing and constructing the campus network, using fast oscilloscopes, splicing fiber, generating, sending, detecting, and monitoring pulses in the picosecond time regime, (2) Expertise was gained in fusion splicing fiber in a functioning network, (3) A capability for sending picosecond duration pulses intense enough for nonlinear interactions to be important over single mode fiber was produced. (4) Some 4 km of fiber were installed providing two complete round trip single mode fiber circuits between the Physics Building and the Ultrafast laboratory. To our knowledge this was the first such capability demonstrated on a university campus.

Within the time constraints of the work we were able to explore and utilize the source laser and the network. With the assistance of Rome Laboratory in the form of a loaned autocorrelator we were able to measure the pulse duration. We were not able to perform work on the portions of the network intended to address experiments on gigabit rate microwave components or multiphase fluid flow. The network was left in place and presumably is still available for future work at Rensselaer Polytechnic Institute. A Ph.D. student, Walter Kaechele, who worked on this project at Rensselaer Polytechnic Institute, is completing his doctoral thesis while working at Rome Laboratory in Rome, NY on synchronization of one of the harmonically modelocked lasers developed in connection with this project with another optical fiber laser. The other fiber laser at Rome Laboratory has been constructed and developed by Dr. Ken Teegarden of Rochester University.

4.1.1 Server site at the Ultrafast Photonics Laboratory

The server site at the Ultrafast Photonics Laboratory provided a source of stable ultrashort pulses at gigabit rates and diagnostic equipment. As part of this effort a harmonically modelocked laser (Fig. 2) was constructed and made fully operational.[3] A Ti:sapphire laser constructed by a student was used to pump the fiber laser for the first portion of the work. A master oscillator power amplifier (MOPA) diode laser was purchased and used to pump the erbium doped fiber laser for the latter portion of the work. The diode laser was significantly more stable and much easier to maintain than the Ti:sapphire laser.

4.1.2 Clock Link

A clock link was constructed between the Ultrafast Photonics Laboratory and the educational laboratory (lecture/lab room) in the Science building. The pulse train directed over the clock link operated at ~ 1.36 GHz and produced pulses of about 40 psec duration. As part of the work pulses from a figure eight laser were sent over the link that had pulse durations of the order of a few picoseconds. The link included four separate strands of single mode fiber. This provided two complete round trip paths from the Ultrafast Laboratory to the lecture/lab room.

Experiments were performed that measured the loss, about 6 dB, in the round trip path. We found, in particular, that mechanical splices produced undesirable loss levels. A single connection box was used approximately halfway along the approximately 800 meter link The single mode fibers were fusion spliced at the junction box. Demonstrations were performed of detection of the pulses using a fast oscilloscope at the lecture/lab location as well as return of the pulses to the Ultrafast Photonics Laboratory.

In general, we found that a low loss, low distortion, link could be installed on campus that permitted transmission, use of signals at the remote site, and return of signals. Students were able to perform the necessary fusion splicing. The round trip link could be, and was, used on a regular basis to monitor signals generated by the modelocked laser and sent over the link at a 1.36 GHz repetition rate. The pulses had approximately the duration, 1-40 picoseconds, and the energy, picojoules, needed to produce solitons.

4.1.3 Data link

A link intended for the use of data sent to a microwave laboratory was constructed. Fiber was installed from the Ultrafast Photonics Laboratory in the Center for Industrial Innovation to the Microwave Laboratory of Professor Borrego in the Jonsson Engineering Center. While four single mode fibers were installed, experiments were not started during the time the laser was operational at Rensselaer Polytechnic Institute.

A link for the application of combined clock and data to the study of multiphase fluid flow was run near the laboratory of Professor Lahey in the Jonsson Engineering Center, but connections were not established to the laboratory. Experiments on this data link were not started during the time the laser was operational at Rensselaer Polytechnic Institute.

4.2 Stable soliton laser

The harmonically modelocked laser shown in Fig. 2 was constructed and made stable by the introduction of a passive interferometer and active feedback stabilization.[3] Both free space and fiber interferometers were introduced, separately, and each was found to operate satisfactorily. The spacing of the interferometers was set to support operation ~ 1.36 GHz. The combination of the passive interferometer and the length control was highly effective in stabilizing the pulse train. The length control was introduced by means of a 20 meter section of erbium doped fiber wound on a piezoelectric controlled cylinder so as to be able to control the length of the fiber laser. The fiber interferometer was less flexible in that the spacing of the effective reflectors could not be changes, but maintained alignment more easily and was much lighter and more compact.

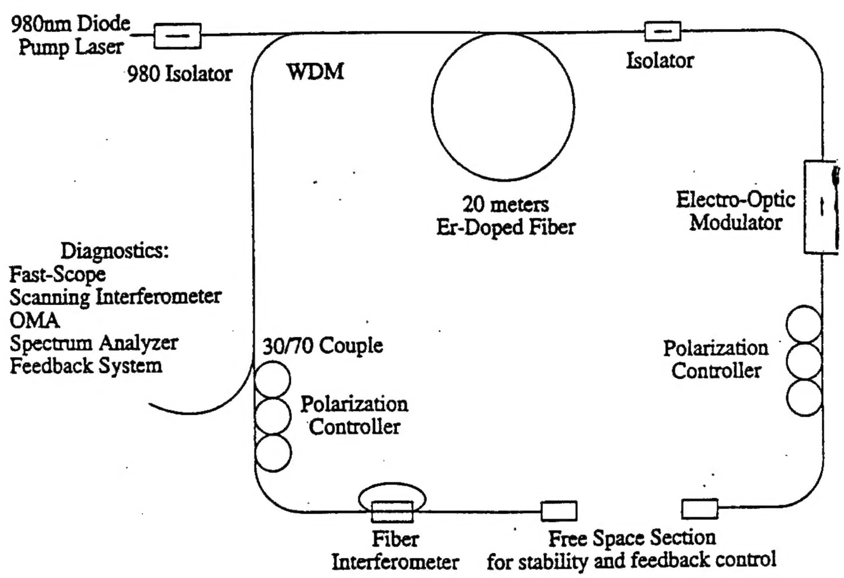

Figure 2. Harmonically modelocked fiber laser at RPI

A spectrum of the output from the laser taken using a scanning interferometer is shown in Fig. 3. The spectral trace was stable as long as the active feedback circuit was maintained operational. This indicates phase stability of the optical fields. In essence the passive Fabry Perot creates a stable resonance. Maintaining the fiber path constant to a small fraction of an optical wavelength maintains a one -to-one correspondence between a particular subset of the laser resonances coincident with the Fabry-Perot resonances. This was, achieved by means of a proportional integrative feedback circuit and related optics.

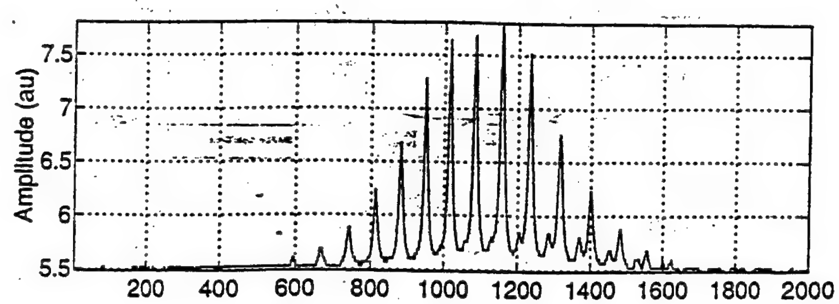

Fig. 3 . Experimentally observed spectrum of fiber laser emission. The mode spacing is 1.36 GHz. The small peaks at the base of the larger peaks are artifacts due to transverse mode coupling. Stable traces were maintained by active feedback stabilization. Larger numbers of modes, and shorter pulses, were obtained, but were not feedback stabilized.

This success was encouraging as regards the feasibility of constructing phase stabilized lasers in general. This is essentially the same laser structure and feedback technique developed by George Harvey and Linn Mollenauer at AT&T Bell Laboratories.[4] One difference is the fiber interferometer that makes the laser lighter and more compact for field applications. We anticipate that these lasers, or lasers with comparable stability, will become increasingly important to optical array systems as phase becomes a more important parameter in complex optical systems. The feedback system used a wedged etalon and a Moire fringe type of strategy developed by George Harvey at AT&T Bell Laboratories. This was satisfactory for the laboratory applications and our pulses of 40 psec duration. We also sent the pulse produced by this laser over a path in the network shown in Fig. 1.

5. Work performed at University of Alabama in Huntsville

5.1 Reconstruction of Ultrafast Laboratory in new location

A substantial effort was invested in moving the Ultrafast Photonics Laboratory from Troy, NY to Huntsville, AL. This move required disassembling much of the equipment and reassembling that equipment again at the Huntsville location. A small amount of the equipment purchased under the AFOSR grant was transferred to Rome Laboratory to assist in setting up a harmonically modelocked laser at Rome Laboratory. The items were a delay line assembly, a configuration of optical components for producing dual signals for the feedback stabilizing network, and a piezoelectric ceramic ring for controlling the length of the erbium doped fiber in the harmonically modelocked laser assembled at Rome Laboratory.

Some of the efforts performed in constructing the new laboratory were: (1) construction of a vibration isolated optical table including a special overhead shelf with electrical power. The shelf was constructed to support a large load and to allow freedom of access to the optical table at all locations around the table, (2) reconstruction of the harmonically modelocked laser originally constructed at RPI, (3) construction of an autocorrelator for measuring the ultrashort optical pulses, (4) construction of a cross correlator, using the same basic configuration, for measuring a pulse perturbed by an optical delay line with a reference pulse, (5) installation of laboratory tables, (6) building of storage cabinets, (7) introduction of means for floating the optical table on air cushioned mounts to reduced vibrations, (8) reconstructing a diode array near infrared spectrometer for observing and recording spectra near 1.55 microns, (9) setting up a fast (25 GHz) detector and oscilloscope for observing the short optical pulses electronically, (10) reinstallation of a signal generator for driving the modulator, and the Mach-Zehnder modulator used to actively modelock the laser, (11) reinstallation of means of control of the modelocked fiber laser pulse polarization by a three paddle control device, and (12) development of means for nonlinear polarization pulse shaping in the laser using quarter wave plates and polarizers and a section of fiber in which the nonlinear polarization rotation was achieved.

5.2 Dual core fiber work

5.2.1 Solitons propagating on dual core optical fiber: experimental

One of the first experimental efforts at the reconstructed laboratory at University of Alabama in Huntsville was a study of the linear and nonlinear properties of short pulses propagating on dual core fiber.[4-6] We obtained samples of dual core fiber from Graham Atkins of the Optical Fiber Technology Center at the University of Sydney, in Sydney, Australia.

We incorporated the dual core fiber in our laser to evaluate the influence of the dual core fiber on solitons propagating within the laser, Fig. 4. The dual core fiber was 20 meters long with a core spacing of about 40 microns. Care was taken to separate the strands and to maintain insofar as possible the orientation of the dual core fiber with a minimum of rotation of the plane of the pair of adjacent cores. The dual core fiber was wound on a large diameter,~1.3 meter, circular frame to minimize birefringence, but also

provide a stable supporting framework for the fiber. The linear coupling from one core to the other was small, but measurable.

We found that the introduction of the dual core fiber section produced a marked reduction in the pulse duration on adjusting the polarization controller in the laser. This experiment did not distinguish, however, between a reduction in pulse duration due to the dual core nature of the fiber or to nonlinear polarization pulse shaping that can occur due to intensity dependent rotation of the pulse polarization ellipse during propagation through the 20 meter section of fiber.

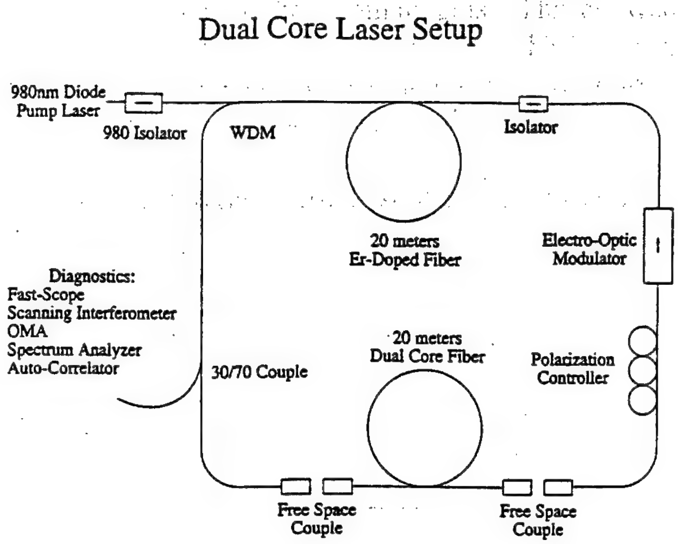

Fig. 4. Harmonically modelocked laser incorporating dual core fiber.

We introduced a similar 20 meter long section of single core fiber to clarify this issue. We found substantially the same pulse shortening with the single core fiber. Our conclusion was that the dual core fiber, in all probability, did not introduce nonlinear shaping mechanisms substantially different from those of single core fiber. These experimental observations agreed with our calculational predictions and the known optical phase delay differences for the two dual core fiber paths.

5.2.2 Solitons propagating on dual core optical fiber: calculational

About this time calculations begun at RPI in connection with this effort were completed. The calculations were performed largely by Sandra Smith Doty, who received her doctorate at RPI for the work.[4] Dr. Joseph Haus and the PI supervised Ms. Doty's work. Those calculations showed a variety of dynamics for solitons propagating on dual core fiber. Some of these dynamics are shown in Fig. 5. In general, for two solitons propagating on the two separate, but adjacent, cores for sufficiently weak coupling there can be bound attractive states (Fig. 5A), repulsive states (Fig. 5B), and neutrally coupled states (Fig. 5C). The repulsive interaction becomes attractive for sufficiently strong coupling so that the general behavior shows only attractive coupled soliton states (Fig.'s 5 D,E,&F).[4]

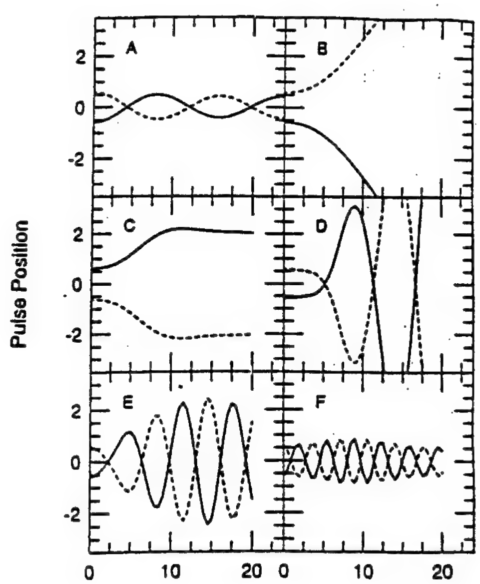

FIG 5

Fig. 5 Relative position of coupled solitons propagating on dual core fiber.

Other work by Yun Je Oh in the theoretical group at Rensselaer Polytechnic Institute showed that under ideal circumstances dual core fiber in a optical fiber laser can result in excellent modelocking and removal of optical noise from the laser.[6] Yun Je Oh received some support under this grant and also completed a doctorate at Rensselaer Polytechnic Institute He was largely supervised by Dr. Joseph Haus. The PI suggested that some of the work be performed as relevant to this AFOSR sponsored project.

About this time we learned from the workers in Sydney who had fabricated our sample of the dual core fiber that they believed the variation in phase delay between the two cores was large compared to an optical period over distances of more than a few centimeters. This uncontrolled variation in phase delay essentially overrides the nonlinear pulse shaping mechanism we sought to study. Given their information, our experimental observations, and supporting evidence from numerical simulations, we suspended our experiments on the dual core fiber.

We note that recent work by Graham Atkins of the Optical Fiber Technology Center in Sydney has demonstrated an optical means of controlling the average phase delay over one core of a dual core fiber doped with a rare earth.[9] In this technique a second beam having a different wavelength than the primary beam is used to partially saturate the rare earth dopant. By varying the degree of saturation of the dopant the average phase delay in one core can be caused to closely approximate the average phase delay in the adjacent core despite small variations in the relative delay between the two cores in the unexcited fiber.

The above experimental approach provides a valuable means of correcting the average relative optical delay along separate cores of dual core fiber. This does not, however, solve the problem of accessing potential advantages of the nonlinear interaction of solitons propagating on dual core fiber. For these distributed interactions to be effective the local phase delay difference must be precisely controlled.

We did not observe the predicted nonlinear interaction of pulses propagating on dual core fiber. As discussed above we believe this was caused by small random variations in the relative phase delay for the two cores that causes the phase relation of the carrier fields of the two pulses to change by a magnitude larger than the variation caused by the nonlinear processes.

5.2.3 Conclusions from dual core fiber work.

Our conclusion from this portion of the work is that there are two relatively strong arguments against using dual core fiber *as such* for maintaining the relative phase and relative envelope position of pulses propagating on adjacent cores of dual core fiber. One argument is that the task of manufacturing and maintaining the relative optical delay on adjacent paths is beyond current capabilities. The other is that even if this demanding device and material task is achieved the nonlinear interactions, see Fig. 5, do not provide a strong stabilizing mechanism. At best the forces between solitons on adjacent cores are neutral and the condition were this neutral coupling occurs is highly specific.

This does not mean that dual and multicore fiber cannot be designed and manufactured so as to produce stabilizing relationships of solitons, or ultrashort pulses, propagating on adjacent cores. It does mean that additional complexity is most likely

required. The PI is pursuing these issues in subsequent work and believes that strategies can be identified. This current work was useful in clarifying some of the problems and some of the tasks that must be addressed in developing a next generation approach.

5.3 Nonlinear polarization rotation modelocked laser.

The work with the dual core optical fiber led to development of a nonlinear polarization rotation modelocked laser. Several factors contributed. Both the calculations and the experimental work indicated that shorter duration pulses were essential. The shortest optical pulses that we routinely obtain are produced by the nonlinear polarization rotation switched laser shown in Fig. 6. We used this laser for experiments on adjustable optical delays. The laser produces pulses of about 2 psec duration with some wings. We hope to reduce these wings and the pulse duration in subsequent work by utilizing more strongly modulated active modulation and more precise length control of the laser resonator. We also expect to add polarization maintaining fiber as a means of stabilizing the polarization and hence the pulses.

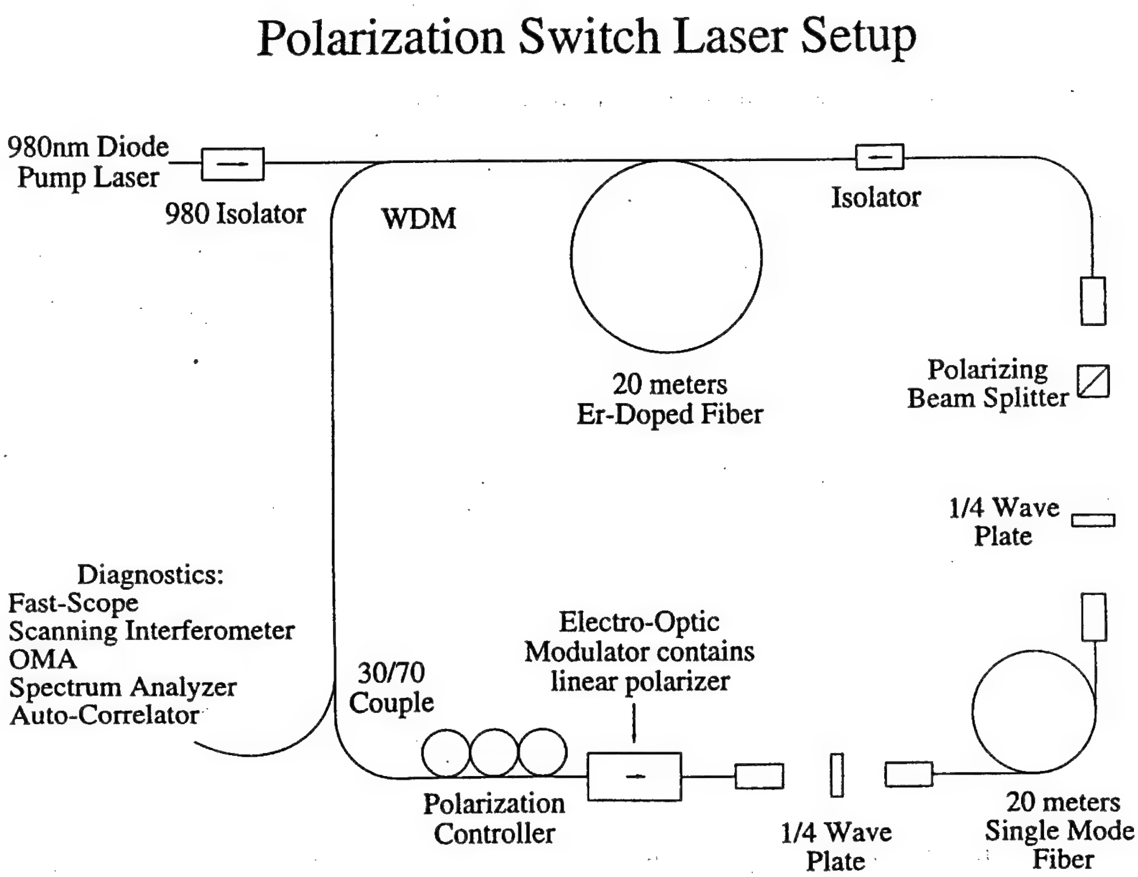

FIG 6

Fig. 6. Harmonically modelocked laser including nonlinear polarization shaping

This approach necessitated coupling the laser beam out of the single mode fiber into free space, propagating the beam distances of order 10cm or more, and then efficiently reintroducing the beam back into the single mode fiber again. This allowed introduction of adjustable free space devices such as polarizers and retarder plates. Considerable care was required in alignment of the couplers. ULTRAlign hardware from Newport was used for the fiber positioning elements. These stainless steel fixtures, specially made for this purpose, were found to be important in maintaining the alignment of the positioning elements over extended periods of time.

A polarization controller composed of three paddles each wound with 2 to3 turns of the single mode fiber was also essential in adjusting the polarization state of the laser field in the single mode fiber. The pulse shortening was usually adjustable around the optimum by adjusting the free space components and this polarization controller. In addition to these elements a linear polarizer was included in the lithium niobate Mach-Zehnder modulator driven by the Hewlett-Packard signal generator and amplifier.

Some pedestal remained on the pulse even for adjustment of the apparatus so as to produce the shortest pulse. We attribute this remaining pedestal to instabilities in the laser. We did develop and implement an active feedback stabilization system for the version of the laser constructed at Rensselaer Polytechnic Institute. We did not have this active feedback system operating in the version of the laser constructed at University of Alabama in Huntsville. A difficulty was that the piezoelectric tuning technology developed to control the length of the laser resonator was loaned to collaborators at Rome Laboratory in Rome, NY for the modelocked laser constructed there. We expect to address this need in the next phase of work.

The work at Rome Laboratory was successful in producing a pair of synchronized lasers. The PI consulted and assisted that work under separate funding. The stabilization strategies were not fully implemented in the Rome Laboratory lasers; however, we expect to work with the personnel there in achieving both stabilization and synchronization.

5.3.1 Polarization maintaining fiber

Given the importance of polarization in shaping pulses and influencing the operation of the laser attention was given to means of stabilizing the polarization state of the laser.[11] Polarization maintaining fiber was purchased and a capability for fusion splicing polarization maintaining fiber added to the laboratory. We intend to include this feature in the next generation of laser developed in the laboratory.

5.3.2 Mechanically adjustable delay line

For adjustment of the laser into the optimally stabilized condition a mechanically adjustable delay line is extremely helpful. A mechanically adjustable delay line was constructed at RPI. The delay line consisted of a simple arrangement of four mirrors and translators that allowed us to adjust the beam path over a distance of order 5 cm. This was not sufficient to tune through the full adjustment range set by the Fabry Perot resonator, but was adequate for the purpose of adjusting the laser under most circumstances. We did not fully implement the active feedback stabilization and the mechanically adjustable delay line at the same time, although each were made to work independently. One mechanically adjustable delay line was loaned to Rome Laboratory for indefinite use.

The adjustable delay line is demanding to align and maintain in alignment. The adjustable delay line is located in the free space region of the laser where small variations in the beam direction can result in large variations in coupling efficiency. The original version of the free space delay line was constructed of four independent mirrors because of time constraints and availability of components. We have, since that time, purchased 180 degree retroreflecting prisms that we plan to incorporate in the next version of the adjustable delay line. The fixed nature of the prisms assists in maintaining the aligned condition.

5.4 Adjustable optical delay using photonic band edge technology.

Given the importance of an adjustable optical delay line to the stable laser, and also the importance of a rapidly adjustable delay line to agile optical phased arrays, we also explored alternative means of producing an adjustable optical delay. We studied a photonic band edge technology that produces orders of magnitude enhancement of the optical delay produced in an electric field controllable device.[7] This technology also causes negligible distortion of the ultrashort pulse and minimal, <5%, unavoidable loss.

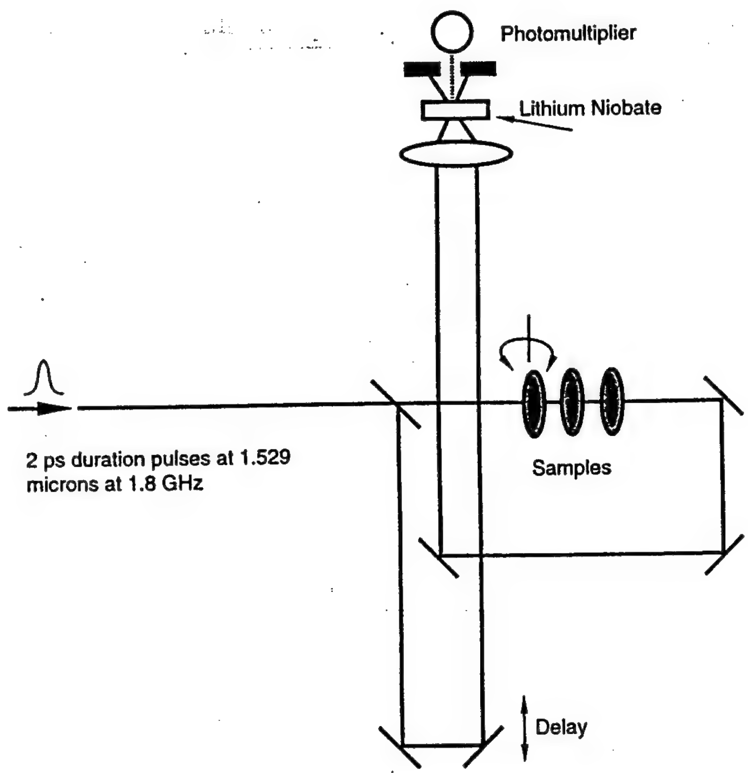

FIG 7a

Fig. 7a. Apparatus for measurement of adjustable group delay in a periodic semiconductor structure.

5.4.1 Large reduction in group velocity

The optical group velocity is reduced by an adjustable amount to a velocity that can be as small as 1/18 of the free space velocity. Larger reductions in group velocity can be achieved in related structures. While the total magnitude of the delay produced in the current structure is modest, order of 100 microns of effective delay, the technology lends itself to integrated optoelectronics that we believe could produce the very large delays needed for practical agile optical phased arrays. See Fig.'s 7 and 8.

5.4.2 Experimental arrangement

The experimental arrangement is shown in Fig. 7a. Pulses of about 2 psec duration were separated into two separate pulse trains by a beamsplitter. The resulting pulse trains were directed through an autocorrelator structure. One train passed through free space. The other train passed through samples of photonic band gap material. The samples could be rotated about their horizontal axis. This rotation, in effect, shifted the band edge relative to the frequency of the incoming pulse. This allowed tuning of the pulse frequency relative to the photonic band edge resonances. This in turn permitted varying the optical delay experienced by the pulses. Provision was allowed for introducing multiple samples in the one arm of the autocorrelator. The optical delay as a function of the orientation of one of the samples is shown in Fig. 7 b. The accumulated delay caused by adding additional samples to the autocorrelator arm is shown in the inset. Provided the samples are separated by the order of the pulse width in free space the additional samples do not cause distortion of the pulses.

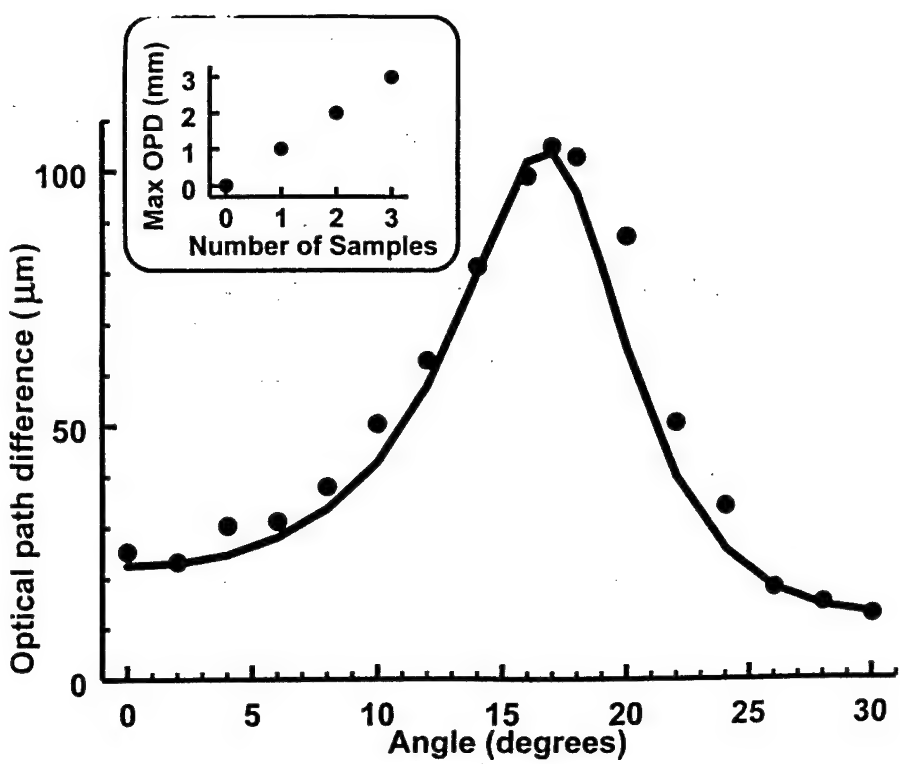

Fig. 7b. Optical delay versus sample orientation for adjustable optical delay.

5.4.3 Physics of the optical delay process

The physics of the adjustable optical delay process can be understood in terms of the coupling of the optical fields of the incident pulses into the photonic band edge structure. The structure and the field distribution is shown in Fig. 8. The figures shown the optical field amplitude at some moment in time. The refractive index profile of the medium is illustrated by the regular periodically varying solid line having right angle transitions at the interface between material of differing refractive index. The fields are shown by the curved traces. The solid line in Fig. 8a shows the electric field amplitude. The dotted line in Fig. 8a shows the magnetic field amplitude.

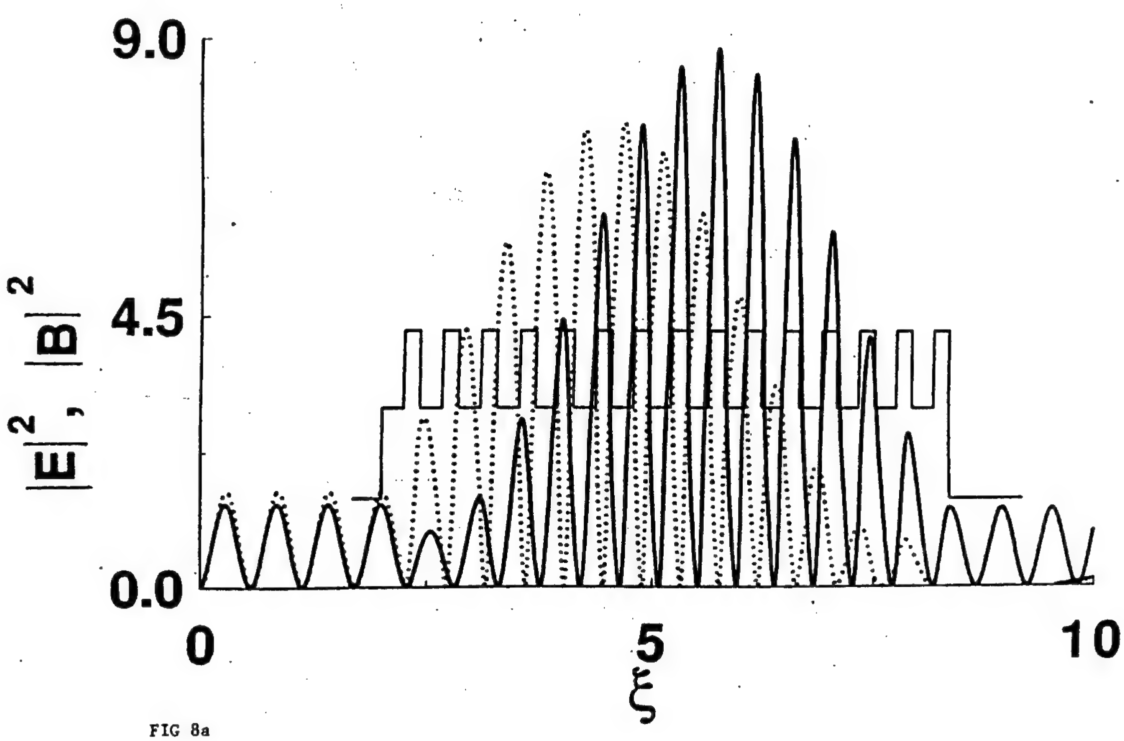

FIG 8a

Fig. 8 a. Plot of intensities for electric (solid) and magnetic (dotted) optical fields in delay structure.

The fields are seen to be periodic with the period of the material. The electric fields, however, peak in the high index regions while the magnetic fields peak in the low index region. This separation of the electric and magnetic fields reduces the Poynting

vector in the material and can be regarded as the cause of the slowing of the optical fields in this region. One can also see the increase in the field magnitude in the periodic structure. This increase in magnitude, in effect, results from a transient storing of optical field energy in the periodic structure that necessarily accompanies the reduction in optical velocity in the structure. Note that only a relatively small portion of the optical pulse is located within the structure at any one instant. In effect the pulse energy moves sequentially through the photonic band gap material.

We plot in Fig. 8b a simulation that assists in the physical understanding of this interesting and potentially useful phenomena. Here the Poynting vector **S** is plotted vs. position in the photonic band edge structure. The positive vertical axis denotes optical momentum ξ directed in the forward direction. The negative vertical axis denotes optical momentum ξ directed in the backward direction. The mean net local optical field momentum (momentum averaged over several periods) is shown by the dashed curve in Fig. 8b. One sees that the incident field carries positive momentum into the structure and, on the average, loses momentum to a circulating wave in the first half of the sample and regains that momentum in the last half of the sample.

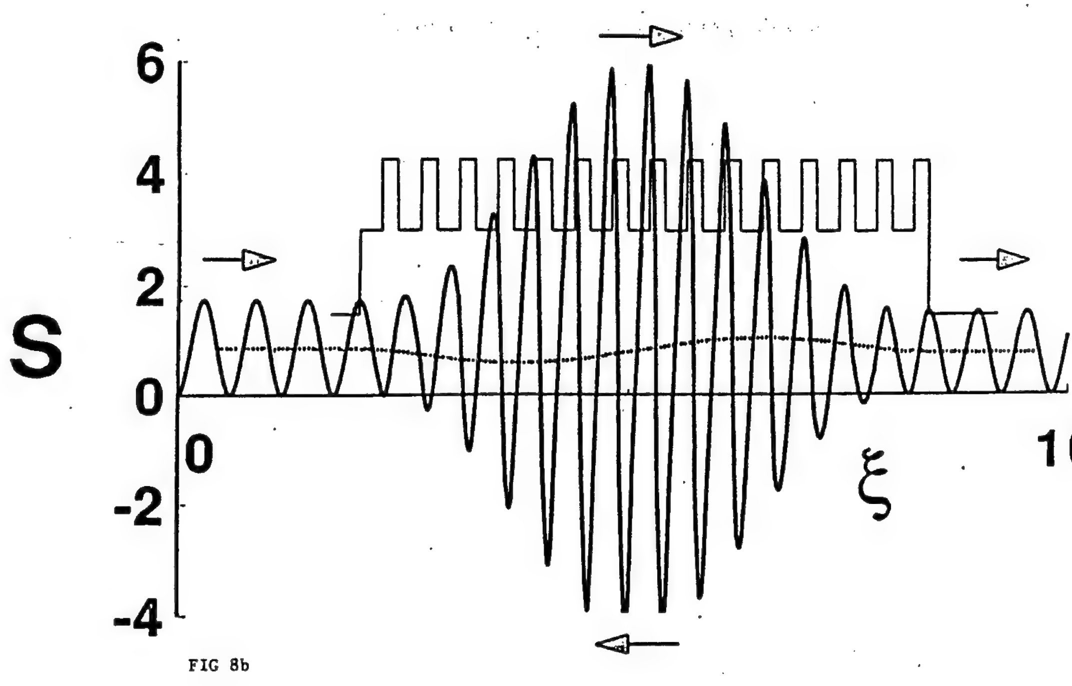

Fig. 8b. Plot of Poynting vector for optical pulse energy. The positive axis denotes momentum to the right. The negative axis denotes momentum to the left.. The dashed line is a local average of the field momentum.

Optical momentum is transiently stored in a circulating optical field within the structure. The remarkable property of this structure is that this transient storage of optical momentum is accomplished with very little backward scattering or distortion of the short optical pulse. In effect, one gains the advantages of an optical resonator while retaining the desirable features of concentrating the optical energy in a short pulse. The pulse enters the structure, is delayed by a time that depends on the relationship of the pulse spectrum and the resonances of the photonic band edge, and then leaves with almost negligible distortion or loss.

5.4.4 Experimental measurements

A number of samples were measured and the observed delay compared with the predicted delay (Fig. 7b). The phenomena is unusual in that the incident pulse is coupled with very little loss or distortion into the periodic structure, remains within the structure for a relatively long period while propagating with a group velocity that is roughly 1/18 of the velocity of light in free space, and is then coupled out of the structure with relatively little loss or distortion. During the time the pulse energy is in the periodic structure the intensity of the pulse fields is increase by nearly an order of magnitude over the intensity in free space. This latter property was not exploited in the work reported on here, but does offer a means of enhancing nonlinear phenomena.

The structure was composed of some 30 alternating layers of GaAs and AlGaAs. The structure was fabricated by Richard Leavitt of Army Research Laboratory. The structure is grown with atomic layer precision by molecular beam epitaxy. The capacity for sample preparation by relatively conventional techniques, the small thickness required, 8 microns, and the potential for fabrication in an array structure are encouraging as regards application of this technology in integrated optoelectronic circuits.

5.4.5 Autocorrelator and cross correlator for measuring time delay

The autocorrelator, and cross correlator used a lithium niobate nonlinear crystal housed in closed cell. The crystal and cell were purchased from Inrad, Inc. The closed cell is valuable in preventing degradation of the crystal due to moisture in the atmosphere. Translation of the stage in the autocorrelator was accomplished using a Newport stage. The Newport translation stage was computer controlled. Mechanical translation of the other stages was accomplished by mechanically adjusted Klinger translators having 15 mm of travel. A dielectric beamsplitter was used to divide the beam into two roughly equal intensity components.

We found that it was possible to measure the pulse peak position with a resolution of 10 femtoseconds or better using this apparatus. We included space in the autocorrelator for semiconductor samples that were measured in the work on the optical delay line. We also included rotatable mounts that allowed us to vary the orientation of the sample normal relative to the direction of the incident beam. This provided a capability for both measuring the autocorrelation function of the short pulse and also for measuring the time delay as a function of orientation introduced by a photonic band gap structure.

5.5 Microresonator and exciton-polariton simulations

5.5.1 Need for enhanced interactions

One of the principal needs in the technology sought for generating and controlling arrays of solitons or soliton-like pulses in a networked environment is a means to rapidly and efficiently control the pulse coded information. We found that the solitons on dual core fiber have too weak an interaction to accomplish the desired control in a reasonable distance. We also found the photonic band edge technology offers significant advantages in that the resonant structure increases the field intensity and consequently the strength of the field-material interaction without unduly sacrificing the properties of the short optical pulses.

There still appears to be a major need to further enhance the light-matter interaction so as to achieve strong interactions in a minimal distance. Recent work by several groups [4,10] has pointed toward the use of exciton-polariton interactions. Where quantum wells, exciton resonances, and microresonator resonances have been optimized evidence has been found of very large vacuum-Rabi frequencies. These structures also show correspondingly enhanced optical emission rates.

In the interest of understanding these phenomena we independently developed a description of the dynamics of these exciton-polariton states. Evidence for these exciton-polariton states has been gathered and developed by a number of well known groups. There seems to be little doubt that these states exist or that they represent a potentially important example of a strong light-matter interaction. There do remain some questions as to the exact nature of these states and their robustness under strong excitation.

We developed simulations of the dynamics of the states in the interest of understanding how these exciton-polariton microresonator states might provide better means of generating and maintaining synchronized and phased arrays of short optical pulses. A key point of interest concerns the means of populating these exciton-polariton states. Two different pumping strategies have been explored. As indicated in Fig 9a and 9b the excitation can be resonant or non-resonant.

5.5.2 Excitation by non-resonant pumping

The successful excitation of these states by non-resonant pumping appears significant in that this implies that incoherent excitation can be used to prepare these coherent exciton-polariton states denoted here by a_1, k_1.[12] Related work has shown that efficient population and gain can be realized at the excitation level of one or a few quanta. The very large interaction between the material system and the optical field combined with the capacity to populate these states by incoherent pumping suggests that these are a useful place to look for the strong nonlinear interactions needed.

We have illustrated the dynamics of one of these exciton-polariton states using a model depicted in Fig.'s 9 a and 9 b. The essence of the physics is that there are a number of wavevector states denoted as a_N, k_N, where a_N denotes the amplitude and k_N denotes the wavevector of the Nth state and the pump energy is distributed among these wavevector states and the external radiation field in a manner describable by rate equations. Although

our picture was developed independently it is quite similar to the picture developed by the Stanford group of Yamamoto.[12]

An important feature is that efficient excitation of the coherent state a_1, can be achieved incoherently as well as coherently. For incoherent pumping the excitation goes into a higher lying state of the system. The excitation is then transferred to the coherent state and to other non-coherent states, N>1, via a dynamical process that depends on the population of the coherent state. The rather surprising finding is that even at low excitation levels this transfer process can proceed with high efficiency.

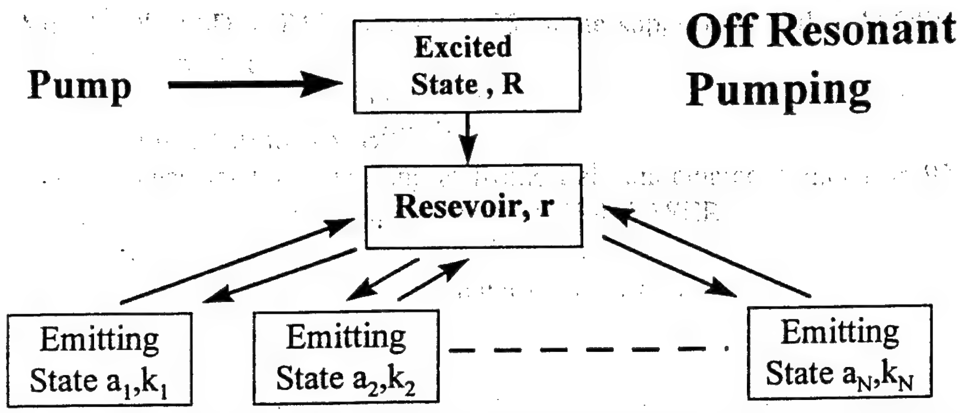

Fig. 9a. Schematic of pumping exciton-polariton with initial pumping into an incoherent state

An alternative pumping strategy, illustrated in Fig. 9 b, is to pump the coherent state a_1, k_1 directly. This requires resonant optical excitation and was one of the first approaches used. The finding that incoherent excitation can be comparably effective in exciting the coherent state is important. Part of our work is directed toward understanding these states and determining the degree to which they may be valuable in achieving high data rate, high parallelism, and synchronous and phase locked operation needed for agile optical phased array technology.

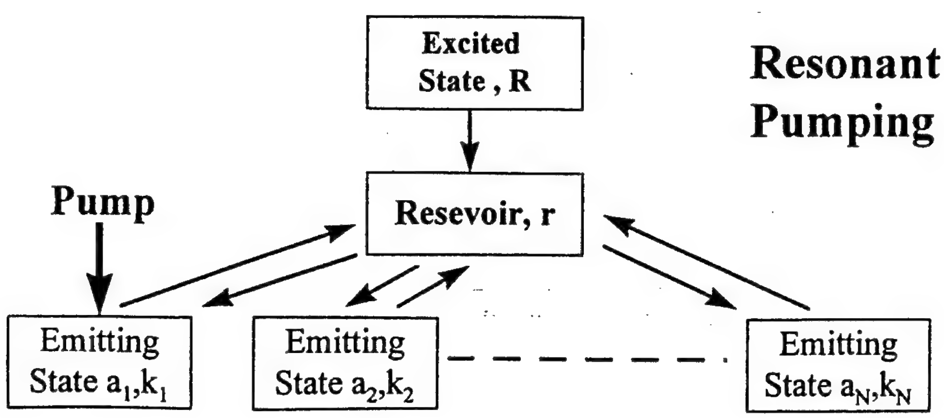

Fig. 9b. Schematic of pumping with initial pumping into a coherent state

5.5.3 Simulations of dynamics

We illustrate some of our findings with the plots shown in Fig. 10a and Fig. 10b. These show the dynamical evolution of the various states. Here the reservoir state is used to identify a state of the system that can be regarded as coupling in some degree with the set of states a_N, k_N. The initial pump excitation is approximated as relaxing to the reservoir state. The excitation then appears in the various alternative states. For some value of the parameters efficient transfer of the original incoherent excitation is transferred to the coherent state a_1. The excitation of the reservoir, a representative incoherent state a_2, and the external radiation field, f_{out}, are also shown.

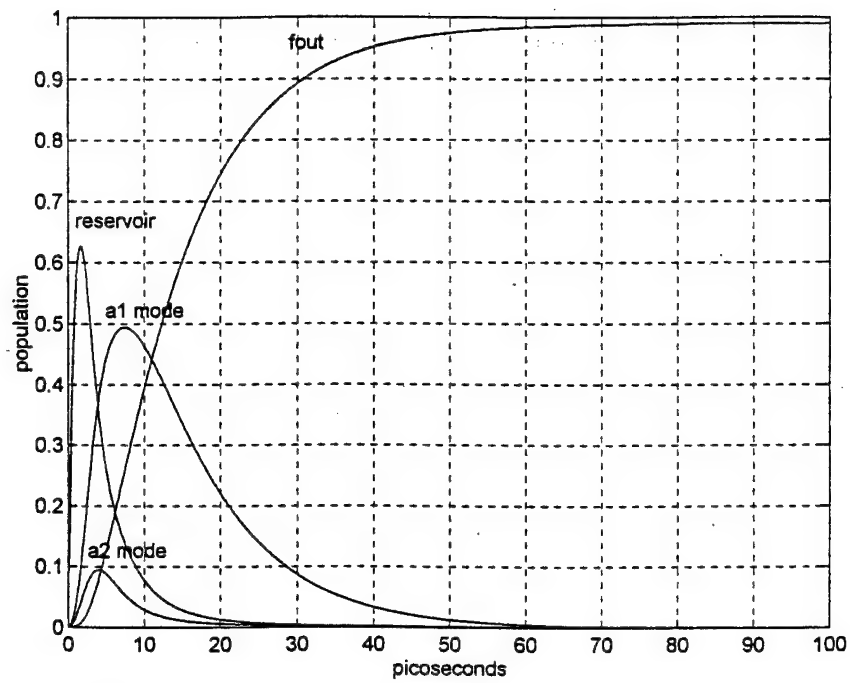

FIG 10a

Fig. 10 a Dynamics of coherent state ,a_1,population for incoherent pumping. The rapid dynamics for only a single quantum excitation are indicative of the strong interactions involved.

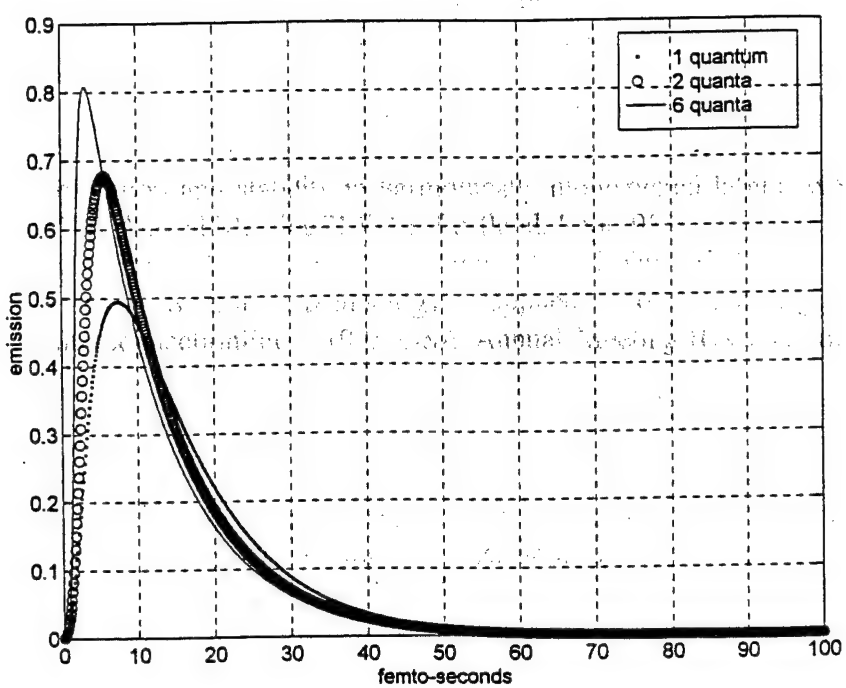

Fig. 10 b. Dynamics of the coherent state as a function of the number of quanta in the excitation. Note the increasingly rapid development with increasing number of quanta.

The example shown in Fig. 10a is for the case of a single quantum excitation. The rate of transfer to the coherent state increases with increasing number of quanta in the system. In Fig. 10b we show that change in the dynamics of the a_1 state as a function of the number of quanta in the system. Increasing the number of quanta increases the rate of population of the coherent state. Perhaps the most important finding, however, is that the population of the coherent state proceeds efficiently and rapidly at very low excitation levels. This may be critical in achieving very agile and flexible high data rate phased array systems.

5.6 Computers and computer applications

Essentially as cost sharing toward this effort a set of computers Digital Equipment Corporation personal computers was purchased by University of Alabama in Huntsville. The computers are to provide computational capability, means for controlling the laboratory apparatus, and a database relevant to the current effort. The also serve other functions such as word processors and data processors. These computers are also used to control laboratory apparatus, such as, the charged coupled linear array detector, the autocorrelator, and the collection and processing of data .

We are developing a Microsoft Access database for this effort that organizes relevant information such as journal articles, calculations, reports, and other material. Typical articles and material deal with fiber optics, ultrashort pulse lasers, soliton, dual core fiber and dual core fiber based devices, simulations of dynamics of microresonators, delay line technology and phenomena, networking, clock recovery, ultrashort pulse detection and measurement, and many other phenomena related to the research effort.

Effort was invested in networking the computers and developing a means for the computers to share a common printer. The computers are linked to the Internet and other computers on campus. We make frequent and diverse use of our access to the Internet via these computers.

5.7 Summary

We have tended to emphasize aspects of soliton based gigabit networks that might be important to the U.S. Air Force. We focused on local networks such as might be found on an aircraft or in agile phased array technology. We particularly examined issues relating to temporally stabilized parallel transmission of solitons and short optical pulses. Key findings relevant to this effort are summarized below.

5.8 Nonlinearly coupled solitons on similar, but distinct optical paths

The idea of using nonlinear interaction of solitons propagating on similar, but distinct, optical paths as a means of obtaining both parallelism and stability of an array of information appears conceptually sound. Numerical simulations show that a wealth of nonlinear interactions occur. At this time, however, a practical problem occurs in that the relative phase delay on physically distinct paths in available media, such as dual core fiber, exhibit uncontrolled variations that override the nonlinear mechanisms of interest.

In essence, the nonlinear interactions that help maintain synchronization are too weak compared to the linear irregularities for this strategy to be useful with existing technology. We essentially conclude that the relative phase variations be made smaller by making the parallel linear paths in the network more regular. Also the nonlinear interactions that favor synchronization should be made stronger per unit path length.

5.8.1 Dual and multicore fiber need improvement to be useful

Dual care and multicore fiber appear to not be particularly useful as such for the proposed application. Free space, or some strategy similar to use of free space such as use of highly uniform material, may be more attractive. Highly uniform dual or multicore fiber could be of interest, but appears difficult to fabricate and maintain.

5.8.2 Adjustable temporal delay in a compact structure with minimal distortion and loss

We unexpectedly found and demonstrated a means of introducing adjustable temporal delay of ultrashort optical pulses with minimal delay and loss in a compact semiconductor structure. This capability is very encouraging as regards advanced soliton or soliton like gigabit arrays in for agile microarea networks such as might be used in aircraft, missiles, or spacecraft. Arrays of such devices may provide a means of controlling the relative position of ultrashort pulses in a low loss precise and agile manner in integrated compact optoelectronics.

5.8.3 Relevance of enhanced nonlinear interactions to coupled soliton based networks

Strong adjustable low loss nonlinear interactions appear important to the goal of gigabit soliton based networks. We found that recent work on excitonic states in microresonators offers encouraging findings as regards very strong nonlinearities in compact structures with gain. While we do not propose a specific strategy at this time, the evidence that incoherently excited states can show both gain and strong nonlinearities at low pump excitation is encouraging.

5.9 General conclusions concerning soliton based gigabit networks

The principal conclusion is that dephasing mechanisms need to be made less important and nonlinear phase controlling and stabilizing mechanisms more important. Active feedback stabilization and enhanced nonlinear interactions, especially in microresonators with gain, offer opportunities. Agile electronic control of phase and group delay in compact structures appear very important and feasible.

We conclude that solitons *per se* are not necessarily needed for stable propagating arrays. Related phenomena such as nonlinear phase and envelope stabilization of individual pulses combined with active feedback for stabilization of the relative phases, are, however, relevant and desirable. Opportunities appear to exist in exciton-polariton states in periodic structures and should be explored.

6. Acknowledgments

I thank Howard Schlossberg for his role as program manager for this project. His availability, interest, and guidance have been essential to this work. I also especially thank George Harvey and Linn Mollenauer for frequently providing valuable guidance regarding the construction and stabilization of the harmonically modelocked laser. Joseph Haus provided a strong theoretical effort that was invaluable in guiding the work on the dual core fiber. Senter Reinhardt performed a great deal of laboratory work that was essential in constructing the feedback stabilized harmonically modelocked laser. He with, Rachel Flynn, did much of the construction of the new laboratory at University of Alabama in Huntsville and they also did much of the experimental work on the measurement of the photonic band gap delay line. Walter Kaechele and Matt Nielsen helped in valuable ways with the harmonically modelocked laser at RPI. Walter also picked up the task begun at Rome Laboratory on the harmonically modelocked laser and continued it to the point of achieving synchronization of pairs of modelocked lasers. Sandra Doty performed valuable theoretical work on dual core fiber. Yun Je Oh was generous in sharing his work on propagation of solitons in dual core fiber and on the dynamics of dual core modelocked lasers.

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8. Participating Professionals and Students

8.1 Names of participating professionals

Joseph Haus, Professor of Physics at RPI, supervised extensive numerical simulation work dealing with the fiber laser pulse generation and interacting solitons in dual core fiber relevant to the project. No direct support from this grant. Some support from Rome Laboratory.

John O. Dimmock, Professor of Physics and director of the Center for Applied Optics at UAH, worked about 10% time for 3 months on model of enhanced nonlinear interactions in microresonators. Received support for this work from this grant.

Michael Jones, Research Associate at UAH. Worked about 5 months on numerical simulation of enhanced nonlinear interaction. No support from this grant. Some support from subsequent AFOSR grant.

8.2 Participating students, degree status and form of support:

8.2.1 Undergraduate students:

Senter Reinhardt, RPI/UAH AASERT, graduated spring 1996
Rachel Flynn, RPI/UAH, ASSERT, expect graduation December 1996
Nick Vitalis, RPI, ASSERT

Chris Young, UAH, AASERT, expect graduation 1997

8.2.2 Graduate Students:

Sandra Doty PhD at RPI completed 1994- discussions and summer support through an ARO AASERT- access to equipment

Kalwant Singh PhD completed at RPI January 1994 support from base AFOSR grant and use of laboratory equipment.

James Theimer (Rome Laboratory) - PhD from RPI in progress - anticipated completion 19965, discussions and some access to equipment, support from Rome Laboratories

Yun Je Oh, PhD at RPI received 1995, some support from this AFOSR base grant, numerical simulations

Matt Nielsen- anticipated completion 97-discussions and access to equipment- limited summer support from AASERT

Walter Kaechele- PhD, working at Rome Lab, anticipated completion 97-discussions and access to equipment, support from AFOSR AASERT.

Darryl Jones PhD Optical Science Program at UAH, completion anticipated 98, support from NASA, some involvement with research program.

8.2.3 Postgraduate Students

Song Wu received his PhD from RPI in1993 working with the PI on the previous AFOSR funding of this project. He participated in some of the work on this project as a postgraduate student and received some funding from this AFOSR grant for that work.

Kalwant Singh received his PhD from RPI working on this project under the PI. Kalwant also continued for about 5 months on the project as a postgraduate student and received support from this AFOSR grant during that time period.

8.3 Students graduated

Sandra Doty received PhD in Physics at RPI in 1994- some support through an ARO AASERT-

Kalwant Singh PhD in EE at RPI January 1994 support from this AFOSR grant

Senter Reinhardt, Undergraduate RPI/UAH AASERT, graduated with degree from RPI spring 1996

9. Visits Facilitating Interactions

Howard Schlossberg, to RPI, March 1994.
Howard Schlossberg, to UAH, August 18, 1995
PI visited C^4I oriented departments at Eglin AFB, 1995
Collaborative work was performed and numerous visits were made by the PI to Rome Laboratories, at Rome, NY.

Visits form NASA personnel and Alliance for Optics in Huntsville

10. Papers published or submitted

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1. R.L. Fork, M. Scalora, Aaron Manka "Physics of coherent emission from photonic band edge, XX IQEC Conference, Sydney, Australia July 1996, paper ThE1
2. R.L. Fork, M. Jones, and J.O. Dimmock, "Coupled near field and radiation field interactions and coherent states in microcrystals", , Nonlinear Optics: Materials, fundamentals, and Applications, Maui, Hawaii, July 1996, paper NpdP11-1.
3. Richard Fork, Michael, Scalora, Rachel Flynn, Senter Reinhardt, John Dowling, Mark Bloemer, Michael Tocci, Chick Bowden and Rich Leavitt, "Ultrashort pulse propagation at the photonic band edge: Large tunable group delay with minimal distortion, , APS March Meeting in St. Louis, 1996.
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1995

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3. Walter Kaechele, R.K. Erdmann, J.W. Haus, and R.L. Fork" Pulse formation and stability in harmonically modelocked lasers, WVV18, 1995 OSA Annual Meeting/ILS-XI, Portland, Sept. 95
4. R.L. Fork, M. W. Maier, J.H. Kulick, S.B. Reinhardt, R.J. Flynn, and J.W. Haus, Soliton technology applied to electronic processor interconnectionFF6 ,, 1995 OSA Annual Meeting/ILS-XI, Portland, Sept. 95

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2. S.L. Doty, Y.J. Oh, J.W. Haus, and R.L. Fork" Dual-core fibers:coupled solutions and amplifiers,ML4, , 1994 OSA Annual Meeting/ILS-XI, Dallas, Oct. 94.

Informal talks also given in 1994 at CREOL at Central Florida University (2), at Williams College, Alabama A&M, UAH, Worchester College, and Rome Laboratories.